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DEFORMATION OF AN ALLOY WITH A LAMELLAR MICROSTRUCTURE: EXPERIMENTAL

By

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HOUGHTON, MICHIGAN U.S.A.

Deformation of an Alloy with a Lamellar Microstructure: Experimental

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The deformation behavior of individual Widmanstatten colonies comprised of aligned lamellae of ductile phases has been investigated. Based on the α-β Ti alloy, Ti-8Aℓ-1Mo-1V, this study shows the existence of a large (>2X) variation in the critical resolved shear stress for yielding of individual colonies. Schmid's Law is not obeyed except for prism slip parallel to the β lamellae. In addition, colonies with a high yield stress exhibit a high work hardening rate and fine, uniform slip, while colonies with a low yield stress deform by planar, non-uniform slip. This behavior appears to be independent of slip system (basal, prism, or pyramidal) and of microstructure (α-β vs. α-α' (martensite)). The experimental behavior is correlated to several colony orientation parameters including the: stress axis, slip plane, slip direction, and orientation of the α-β interface. The yield stress of a colony is found to increase as the slip direction of the dominant macroscopic slip plane tends toward being normal to the α-β interface.

These results indicate that the macroscopic flow behavior of colonies comprised of ductile lamellae depends on the ability of a slip system, once activated in the softer phase, to shear through the harder phase. The data also indicate that the interaction stresses at the phase interfaces are not a principal factor controlling macroscopic yielding. Finally, the alignment of a slip system in the α-phase with a potential slip system in the β-phase lamellae does not appear to affect the yield stress strongly.

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INTRODUCTION

Many alloys possess a microstructure which contains colonies comprised of a mixture of phases with a lamellar morphology. Some typical examples are the α-β Ti alloys in the β-annealed condition, steels containing pearlite, and some directionally solidified eutectics. While certain features of the deformation of such alloys are well established, relatively little is known about the deformation behavior of individual colonies. It is well known that some, but not all, colonies with a lamellar microstructure are susceptible to very planar, non-uniform slip which can lead to easy crack initiation and propagation along such localized bands, particularly in α-β Ti alloys[1-6] and pearlitic steels.[7-12] Even though it may be confined to a few isolated colonies, such behavior can limit the overall ductility and fatigue resistance of a component. There has been no experimental study which identifies the relationships between a microstructure consisting of aligned lamellae of two deformable phases and the resulting deformation behavior for individual colonies. Utilizing the α-β Ti alloy, Ti-8Aℓ-1Mo-1V, this investigation examines the deformation behavior of thirty-seven individual colony test samples. The yield strength, work hardening behavior, and the slip characteristics will be related to several microstructural parameters, such as the orientation of the colony to the stress axis and the crystallography of slip. Since the β phase can be transformed to a martensite if a colony is quenched from 927°C or retained as bcc β if quenched from 760°C,[13-16] the influence of heat treatment is also explored. Particular attention will be given to relating these results to the calculations of Ankem and Margolin on the role of elastic interaction stresses on the onset of plastic flow for oriented two ductile phase structures.[16] The Ti-8Aℓ-1Mo-1V alloy ("Ti-811") is used as a model system because it is relatively well characterized; the nature of the individual phases can be manipulated, and it is much easier to grow rather large α-β Widmanstatten colonies in this alloy than in other α-β Ti alloys, such as Ti-6Aℓ-4V.

EXPERIMENTAL PROCEDURE

The preparation of large colonies consisting of relatively well aligned α and β lamellae is difficult in Ti alloys because the microstructure is a result of a solid state reaction on cooling from through the β transus at $\sim$1050°C to the $\alpha + \beta$ phase field. Strips of Ti-811 approximately 76mm long by 25mm wide were cut from 1.27mm thick sheet. The strip length was parallel to the rolling direction. After cleaning, large α-β colonies were grown by β annealing the strips at 1400°C for six hours and cooling slowly to 1050°C over a period of one hour. At that point the strips were cooled to 930°C at a rate of about 18°C/hour, then cooled to 760°C at a nominal rate of 90°C/hour, and finally furnace cooled to room temperature. All heat treating was performed in a dynamic vacuum of lower than 1.3×10^{-4} Pa. This tedious process produced α-β Widmanstatten colonies of sizes up to $\sim$13mm in diameter and through the thickness of the sheet.

Compression test samples in the form of rectangular parallelpipeds of final size of 1.3mm x 1.3mm x 3.4mm were obtained by cutting samples from large colonies, carefully hand grinding, and electropolishing in a solution of 59.4% methyl alcohol, 34.6% n-butyl alcohol, and 6% perchloric acid at -30°C. The samples were then wrapped in Ti foil, encapsulated, and heat treated at either 927°C/2 hours, 843°C/2 hours, or 760°C/2 hours. The capsules, which contain He as an exchange gas, were water quenched after heat treatment. The end faces were then ground flat and parallel using a fixture which resulted in a final length of 3.43mm. The orientation of the α-phase was determined by a Laue back reflection method, and the orientation of the β lamellae to the stress axis was obtained by a two surface analysis. The as-prepared samples had a composition of (in wt. %): Ti-7.9 Aℓ -1.0Mo-1.0V. Interstitial content in wt. ppm is: 1400 oxygen, 230 carbon, 28 nitrogen, and 13 hydrogen.

Compression testing was performed on an Instron testing machine at a nominal strain rate of 2.5×10^{-4} sec^{-1}. Tests were discontinued at 6-8%

axial strain or less. Quantitative metallography was used to determine slip line spacings, and the active macroscopic slip plane(s) was determined by two surface analysis.

RESULTS

Figure 1 shows the lamellar microstructures of Ti-811 Widmanstatten colonies used in this investigation. The 927°C solution-treatment produces an α (hcp) - α' (orthorhombic martensite) structure with the martensitic being internally twinned.[14,15,17] In the present case, the volume fraction of α' is about 18%. The solution-treatments at 843°C and 760°C should both produce α (hcp) - β (bcc) microstructures with possibly a trace of α' after the 843°C heat treatment.[13,14] The volume fraction of β is about 12% and 10% for the 843°C and the 760°C solution treatment respectively. Because of the water quench, α_2 precipitates are not expected to form.[13] The "interface phase" is expected to form as a layer between the α and β phases after the initial cooling during colony growth.[18-20] However, the subsequent heat treatments, especially the 843° and 927°C treatments, probably destroy the interface phase,[21] although no direct measurements were made. The interlamellae spacing was ∿6.5 x 10^{-3} mm for all of the samples; no attempt was made to alter it.

The orientation of the stress axis of individual Widmanstatten colonies designated with respect to the crystallography of the α-phase is shown in a standard hcp (0001) stereographic triangle in Fig. 2. Figure 3 depicts the orientation of the normal to the β/α' lamellae* assuming that the stress axis is in the position shown in Fig. 2. Thus the combination of Figs. 2 and 3 permits one to determine the angles between the following directions:

*Both the α' lamellae (927°C solution-treatment) and the β-phase lamellae (845°C and 760°C solution-treated samples) are designated as β in the remainder of this paper, except where behavior specific to the martensitic α' is discussed. The same procedure will be used with regard to the presence of the interface phase.

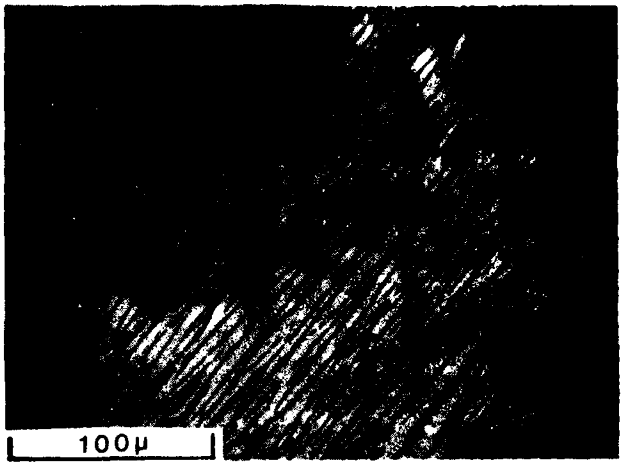

Fig. 1. An optical micrograph showing the aligned Widmanstatten microstructure of the Ti-8Aℓ-1Mo-1V colonies examined in this study. The microstructure is α-β given the 760°C/2 hrs. heat treatment.

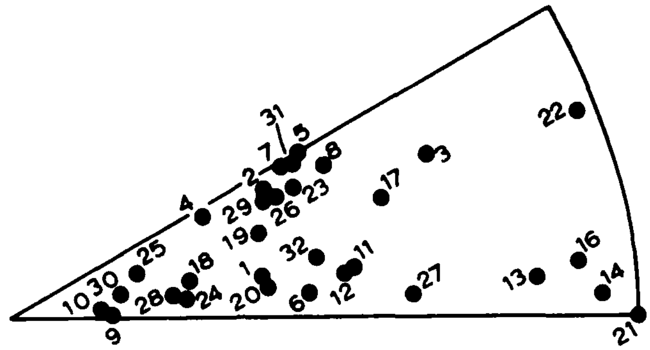

Fig. 2. The orientation of the stress axis of individual Widmanstatten colonies tested in compression. The designations are with respect to the crystallography of the hcp α-phase.

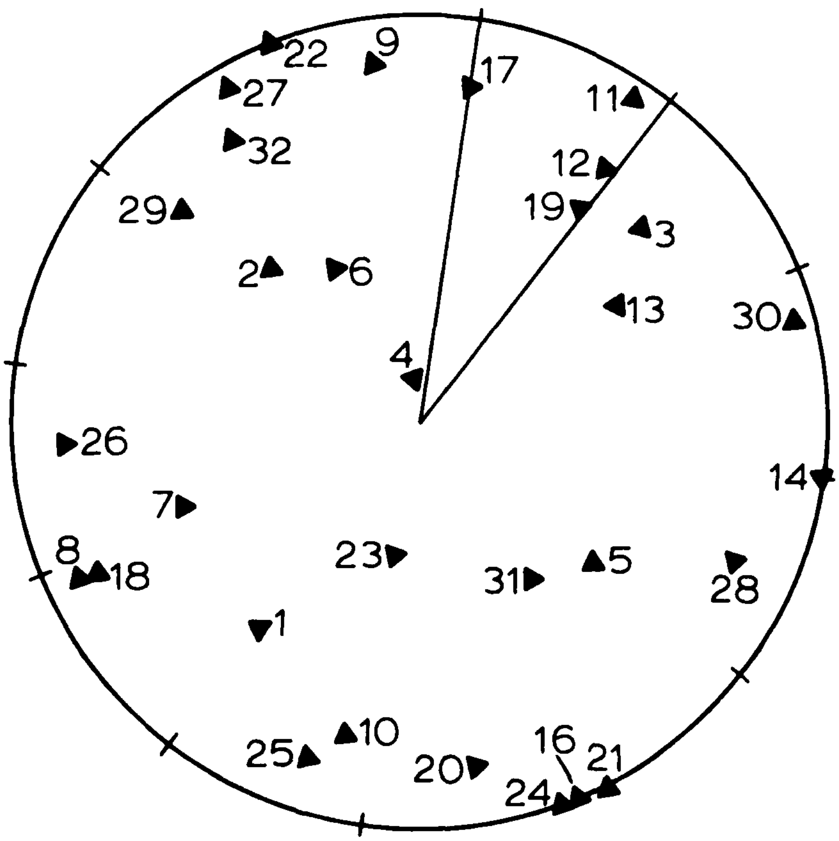

Fig. 3. The orientation of the normal to the α-β (or α-α') lamellae interface. This Figure is based on the stress axis in the position shown in Fig. 2.

ϕ - the slip plane normal and the stress axis,

λ - the slip direction and the stress axis,

β_s - the slip plane normal and the normal to the β lamellae (i.e., the α-β interface),

β_b - the slip direction and the β lamellae normal, and

β_{sa} - the stress axis and the β lamellae normal.

The results of all of the compression tests of the individual colony specimens are tabulated in Table I. Aside from the colony orientation parameters, both the axial yield stress σ_y (at 0.5% offset strain) and the resolved shear stress at yielding τ_y (from $\tau_y = \sigma_y \cos\phi\cos\lambda$) are also included in Table I. Individual colonies deform usually by slip on a single, macroscopic (i.e., as observed by optical microscopy) slip system, which may involve either the (0001) basal, a $\{10\bar{1}0\}$ prism, or a $\{10\bar{1}1\}$ pyramidal slip plane. Twinning or $(\bar{c} + \bar{a})$ slip was never observed. Slip directions were not determined experimentally; slip was assumed to occur in the most highly stressed slip direction. It should be noted that slip on all three slip systems was individually active in samples heat treated at 760°, 843°, or 927°C heat treating temperatures.

Inspection of Table I and Fig. 4 shows that both the axial yield stress σ_Y and the critical resolved shear stress τ_Y of individual colonies are strongly dependent on colony orientation. This effect reflects the behavior of not only (0001) slip but also $\{10\bar{1}0\}$ and $\{10\bar{1}1\}$ slip (see Fig. 4) and appears to be independent of heat treatment. Thus, most individual colonies do not obey Schmid's Law; i.e., yielding does not occur in a single colony at a critical value of the shear stress on a given slip system unless slip is parallel to the β phase (see $\{10\bar{1}0\}$ slip in Fig. 4). Although it is not directly indicated in Table I, the macroscopic slip plane often has a Schmid factor ($\cos\phi\cos\lambda$) which is substantially smaller than several other more highly stressed slip

Table 1. The dependence of the axial yield stress σ_y, the critical resolved yield stress τ, the work-hardening rate $d\sigma/d\varepsilon$ and the average slip line spacing d on various colony orientation parameters which describe the crystallography of slip and of the microstructure of individual α-β or α-α' Widmanstatten colonies of the alloy Ti-8Al-1Mo-1V.

Sample	Annealing Temp., °C	Macroscopic Slip Plane	Colony Orientation, Degree					σ_y, MPA	τ_y, MPA	$\frac{d\sigma}{d\varepsilon}$, MPA	d, mm
			ϕ	λ	β_a	β_b	β_{sa}				
1	927	$(10\bar{1}0)$	62	55	63	38	68	862	234	2930	.0040
2	927	$(10\bar{1}0)$	50	70	82	37	40	744	165	1470	.0031
3	927	$(10\bar{1}0)$	43	54	70	24	30	1220	524	2350	—
4a,4b	927	$(10\bar{1}1)$	50	58	66	78	32	772 820	263 279	1800 1500	.0039
5	927	$(10\bar{1}0)$	48	61	44	64	90	800	255	460	.0070
6	927	$(10\bar{1}1)$	49	48	90	54	48	820	358	2760	.0027
7	927	(0001)	53	37	66	62	87	731	352	950	—
8	927	$(10\bar{1}0)^+$	63	39	10	85	72	724	255	70	.0155
9	927	(0001)	17	75	83	16	72	1613	407	10,100	.0037
10	927	(0001)	15	76	81	27	83	1585	365	11,000	.0043
11	843	(0001)	56	40	86	24	30	800	352	280	.0270
12	843	(0001)	54	42	78	30	25	793	352	70	.0490
13	843	$(10\bar{1}0)$	56	36	82	32	32	724	331	770	.0038
14	843	$(10\bar{1}0)^+$	59	33	0	90	56	655	283	70	.0056
16a,16b	843	$(10\bar{1}0)^+$	55	37	0	90	55	634 634	289 289	219 219	.0090
17a,17b	843	$(10\bar{1}1)$	55	46	63	28	20	723 731	288 291	1180 950	.0017
18	843	(0001)	31	61	83	62	72	765	317	1190	—
19a,19b	760	$(10\bar{1}1)$	48	48	68	24	26	937 855	420 383	2380 2720	.0059
20	760	(0001)*	48	48	81	20	62	779	352	1150	.0390
21	760	$(10\bar{1}0)^+$	60	30	0	90	60	648	276	280	.0128
22	760	$(10\bar{1}0)^+$	40	50	0	90	40	531	255	70	.0119
23a,23b	760	(0001)	52	38	37	53	90	579 634	281 308	90 106	.0540
24	760	(0001)	31	62	90	30	72	958	386	4890	.005
25	760	(0001)	24	66	87	14	72	1158	427	4950	—
26	760	(0001)	50	40	82	74	82	634	310	480	.049
27	760	$(10\bar{1}0)^+$	60	40	8	82	66	620	236	210	.0290
28	760	(0001)	29	68	80	46	80	924	305	7260	.003
29	760	(0001)	48	42	86	58	82	572	286	270	—
30	760	(0001)	16	76	88	7	77	1937	446	—	—
31	760	(0001)	56	34	50	56	84	662	304	60	.0458
32	760	(0001)	52	40	80	42	62	613	288	280	—

Key:

- * indicates that cross-slip also occurs
- \+ denotes that slip is parallel to the β lamellae

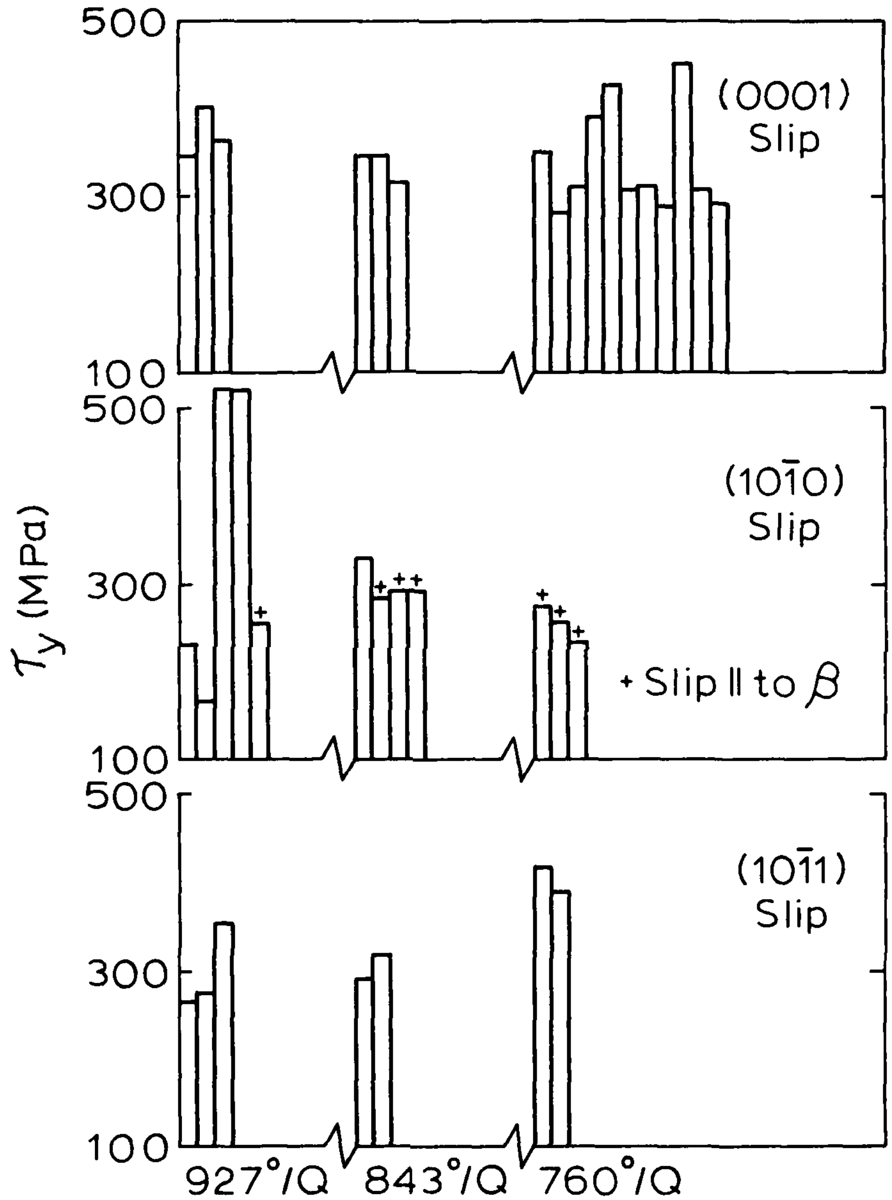

Fig. 4. The critical resolved shear stress of the individual colonies as a function of the active macroscopic slip plane and prior heat treatment.

systems. In many cases, the shear stress on the highly stressed, "non-active" systems is sufficient to activate macroscopic slip in other samples. For example, sample 1 shows macroscopic slip on a prism plane with a Schmid factor of $\cos\phi\cos\lambda = 0.27$ and $\tau_y = 234$ MPa. There are three other slip systems in this same sample which: (a) experience larger shear stresses and all of these should be active since the shear stress τ exceeds τ_y for that slip system in another sample (for example, the (0001) $[11\bar{2}0]$ slip system has $\tau = 386$ MPa, but (0001) slip was activated in sample 10 at $\tau_y = 352$ MPa).

Individual Widmanstatten colonies show large variation in stress-strain behavior. Figures 5 and 6 depict the shear stress-shear strain curves for several individual colonies solution-treated at 927°C and at 760°C respectively. It should be noted that the shear strain indicated in Figs. 5 and 6 is an average value along the length of the colony. From Figs. 5 and 6 it is evident that individual Widmanstatten colonies exhibit large differences in the work hardening behavior as well as the yield strength. In the regime of plastic strain range investigated in this study (a maximum of 8% axial strain), most of the colonies exhibit linear work-hardening. The magnitude of the linear work hardening rate $d\sigma/d\varepsilon$ varies greatly from colony to colony, ranging from 70 to 11,000 MPa (see Table I). Contrary to the usual flow strength-work hardening relationships in alloys, Fig. 7 indicates that in these α-β colonies, <u>$d\sigma/d\varepsilon$ tends to increase with increasing yield stress</u>. Furthermore, at a given strength level, there is also a substantial variation in work hardening rates, as illustrated by samples 28 and 33 in Fig. 6. This gives rise to the "scatter" band shown in Fig. 7.

The yield stress and work hardening behavior described is quite reproducible providing that the colony orientation parameters of two samples are identical. For example, samples 3, 4, 16, 17, and 23 all involve duplicate tests of two identical samples. Inspection of the resulting data in Table I indicates good reproducibility of the observed behavior. Thus the trends noted cannot be caused

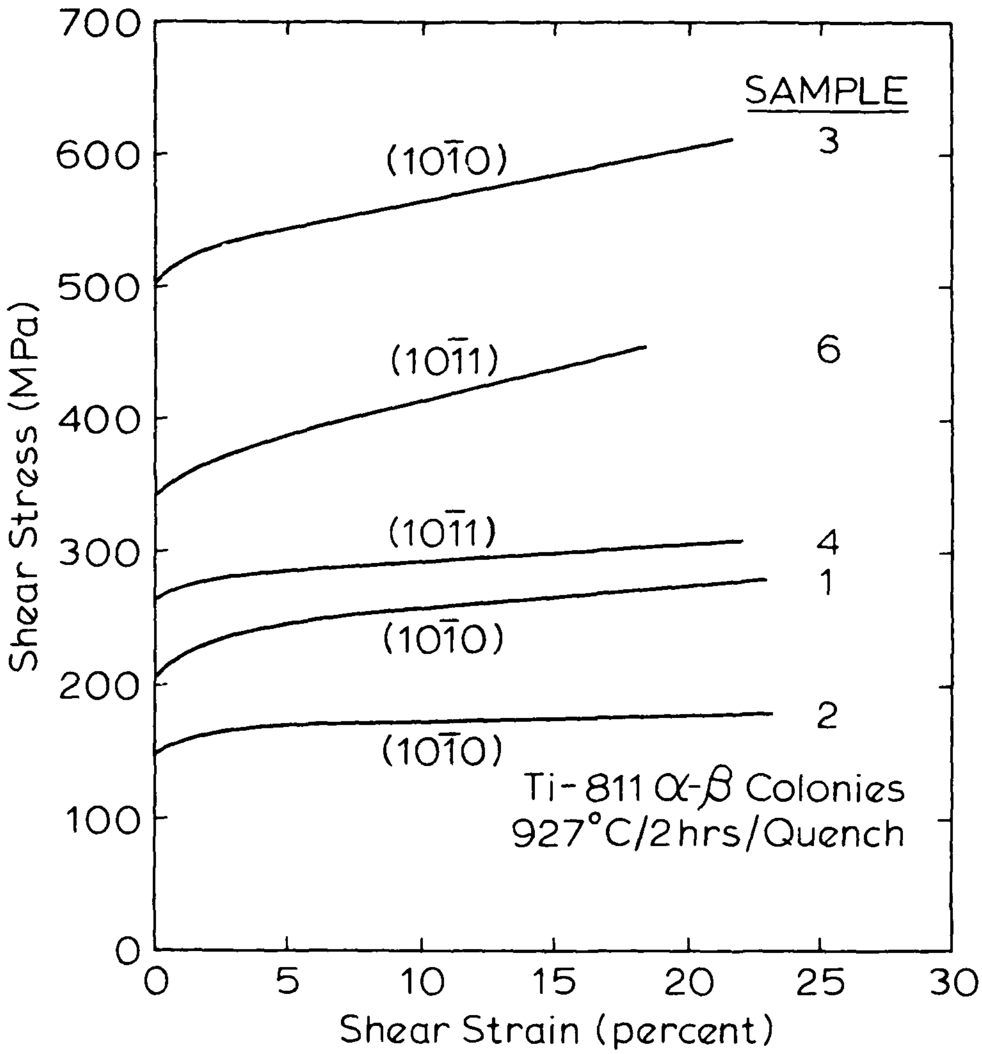

Fig. 5. Stress-strain behavior for selected α-α' colonies heat-treated at 927°C and quenched. Tested at room temperature and in compression.

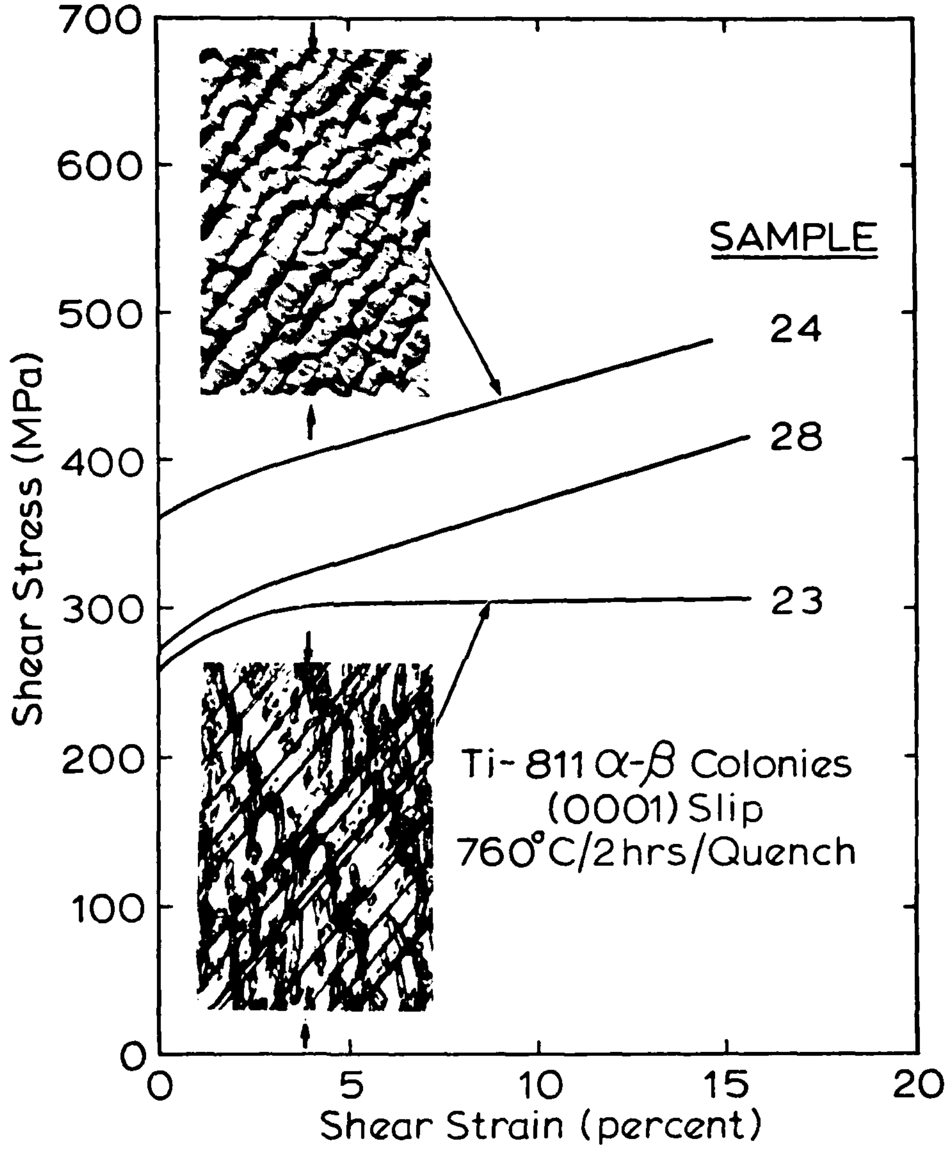

Fig. 6. Stress-strain behavior for α-β colonies heat-treated at 760°C and quenched.

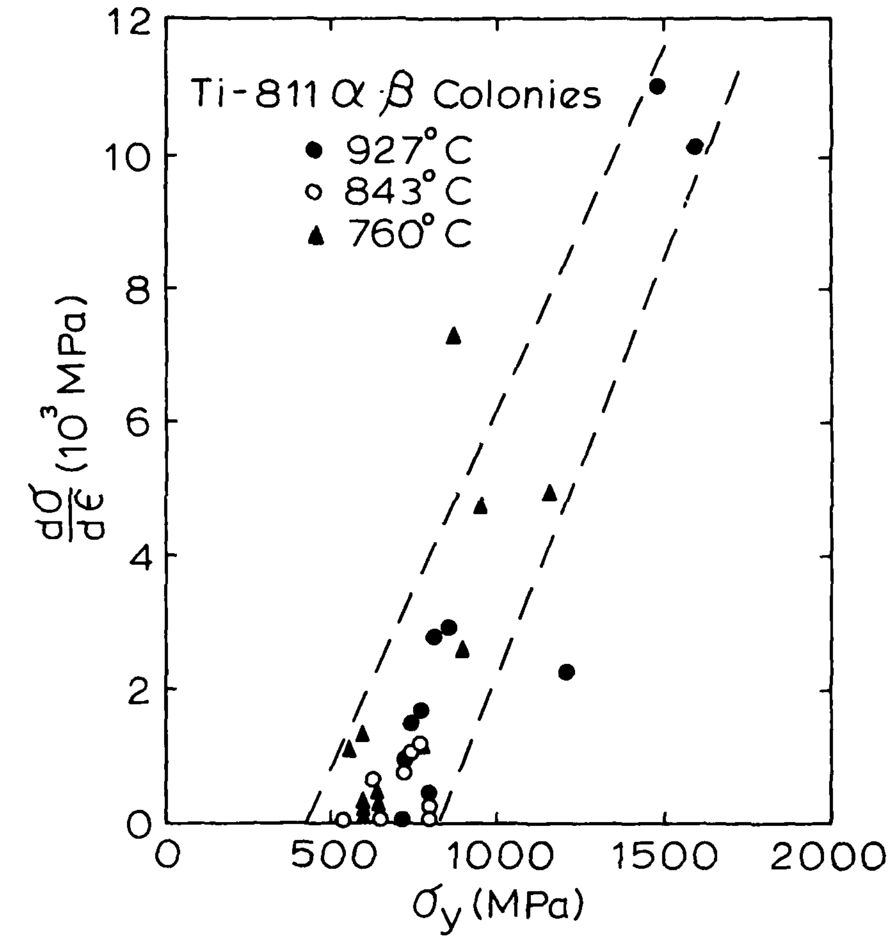

Fig. 7. The relationship between the work hardening rate $d\sigma/d\varepsilon$ and the axial yield stress of individual α-β and α-α' colonies.

by sample to sample variations.

The slip morphology of Ti-811 Widmanstatten colonies varies greatly from sample to sample and can be characterized into three categories: namely, non-uniform flow with coarse planar slip across a α-β colony; fine, uniform slip observed mainly in the α-phase but across a colony; and finally, non-uniform slip which is nearly parallel to the β lamellae and which occurs almost exclusively in the α-phase. Except for sample 20, all colonies deform by slip on a single macroscopic slip system. Figure 8(a) depicts an individual colony exhibiting non-uniform flow in the form of coarse, planar slip. This type of inhomogeneous slip is typical among colonies with low yield stress, low work-hardening rate, and large slip line spacings ($d > .007$mm). The characteristics of this type of plastic flow are the repeated shearing of the β lamellae and the formation of intense, planar slip bands resulting in large slip band spacings and shear offsets caused by each slip band. In the other extreme, colonies exhibiting fine, uniform slip show high yield stress, high work-hardening and small slip line spacings, an example of which is shown in Fig. 8(b). In some cases, slip was so fine that it could not be resolved in the optical microscope. Fine, uniform slip is usually observed in only the α-phase; while the macroscopic shape change of a deforming colony indicates that β had deformed, no slip or twinning markings could be observed even in the scanning electron microscope.

Figure 9 shows that, as a general trend, colonies exhibiting fine, uniform slip with small ($\leq .004$mm) slip line spacings exhibit high work hardening rates and vice versa. The wide range of slip uniformity illustrated in Fig. 9 is exhibited by samples deforming by both basal and prism slip (there is not sufficient data on pyramidal slip to make any generalization). When the average slip line spacing is large ($> .01$mm) Fig. 9 shows that $d\sigma/d\varepsilon$ becomes negligibly small (< 250 MPa) and work hardening is then independent of slip line spacing.

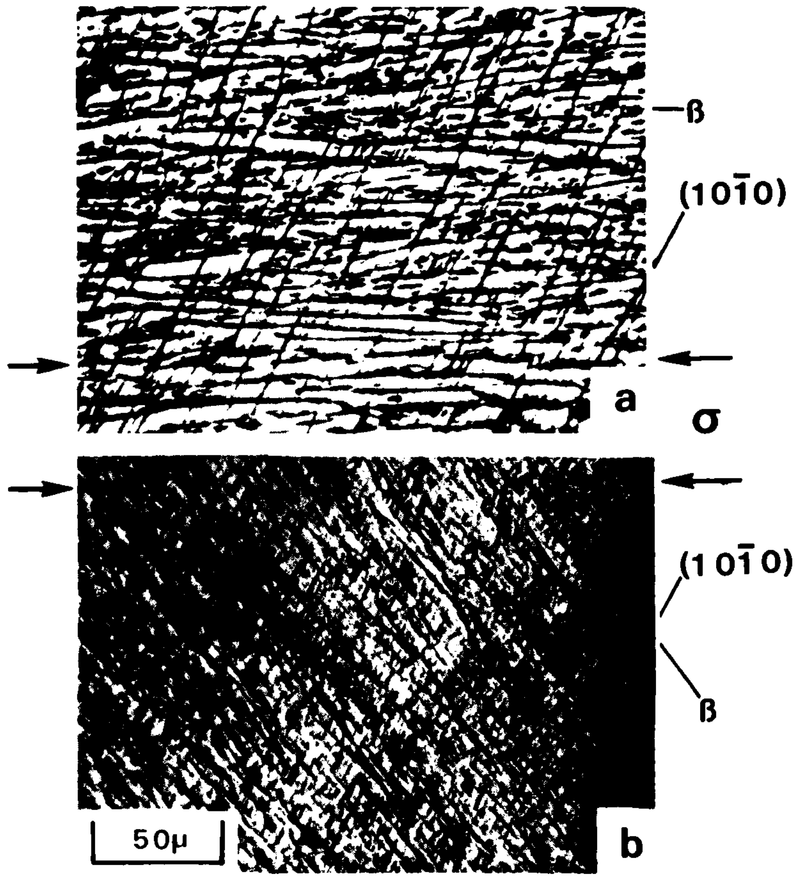

Fig. 8. Slip lines on colony surfaces depicting a range of slip behavior from (a) planar, non-uniform slip (sample 5) to (b) fine, uniform slip (sample 1).

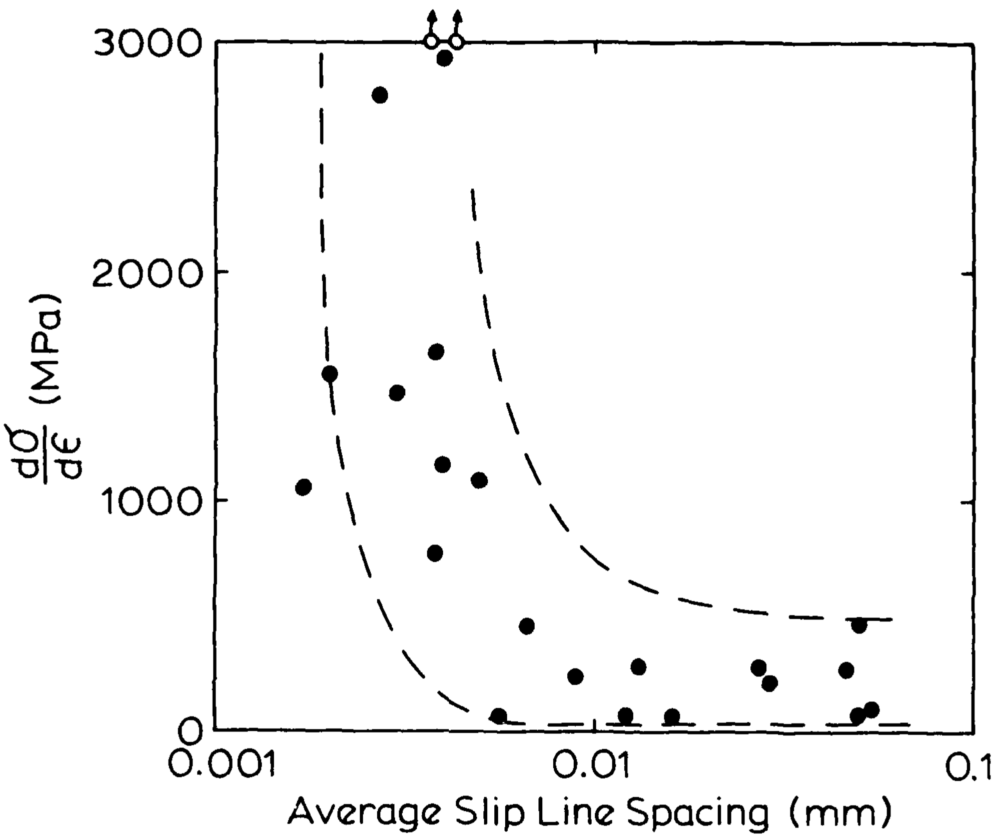

Fig. 9. The dependence of the work hardening rate on the average slip line spacing for individual colonies.

Slip on a $\{10\bar{1}0\}$ plane in the α-phase parallel to the β was observed in a number of colonies (samples 8, 14, 15, 20, 21, and 26). Individual colonies exhibiting macroscopic slip parallel to the β lamellae possess low yield stresses as well as a low work hardening rate ($d\sigma/d\varepsilon \leq 280$ MPa). Unlike samples which yield by slip across the α-β lamellae, the seven samples deforming by $\{10\bar{1}0\}$ slip parallel to the β-phase obey Schmid's Law with an average critical resolved shear stress of 269 MPa (and a range of 236-289).

The yield stress of individual Widmanstatten colonies is found to be dependent on the angle β_b, the angle between the slip direction and the β lamellae normal. Figure 10 shows that as the angle β_b decreases in the range of $\beta_b \leq 45°$, the axial yield stress σ_y increases rapidly. The lowest yield stress is observed $\beta_b = 90°$ in which case slip occurs parallel to the β lamellae. Conversely, the largest yield stress occurs when the slip vector is nearly perpendicular to the β lamellae. The dependence of yield stress on the angle β_b is observed in all colonies, regardless of active macroscopic slip plane or of heat treatment. There is virtually no effect of annealing temperature on the observed behavior. At most, the data in Fig. 10 suggests that the 927°C samples ($\alpha + \alpha'$) may exhibit about a 20% higher yield stress than do the α-β samples heat treated at 760° or 843°C. Figure 11 shows that the critical resolved shear stress τ_y also depends on β_b in a manner similar, although not as pronounced, to that of σ_y. Thirty-five of thirty-seven colonies obey the trend lines shown in Fig. 11 which indicate that <u>both σ_y and τ_y decrease with increasing β_b</u> even at varying values of β_s and β_{sa}.

Several cross plots of data in Table I were attempted to establish relationships between σ_y or τ_y and the other colony orientation parameters, β_{sa} and β_s. Figure 12 shows that τ_y does not depend directly on β_{sa}, the angle between the normal to the β lamellae and the stress axis. In other words, the orientation of the lamellae to the stress axis does not, solely by itself, appear to influence

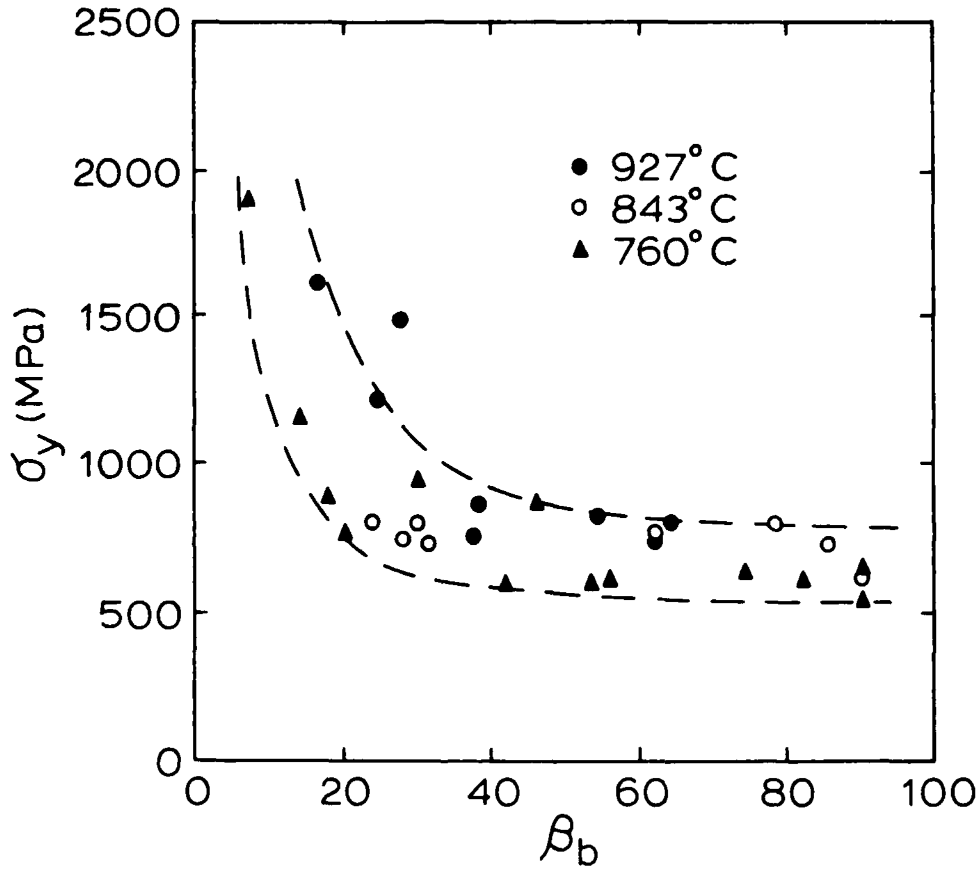

Fig. 10. The dependence of the axial yield stress σ_y on the angle β_b between the slip direction and the normal to the α-β interface.

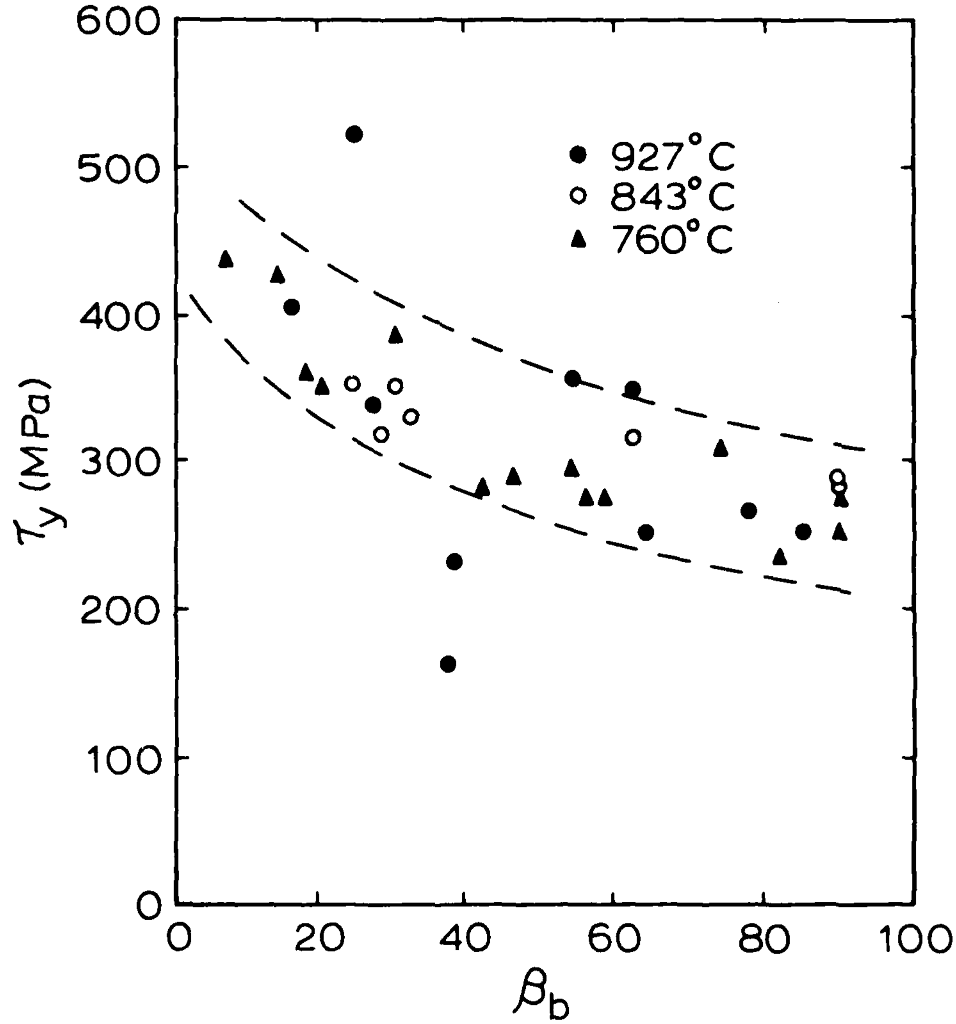

Fig. 11. The dependence of the critical resolved shear stress τ_y and the angle β_b between the slip direction and the normal to the α-β interface.

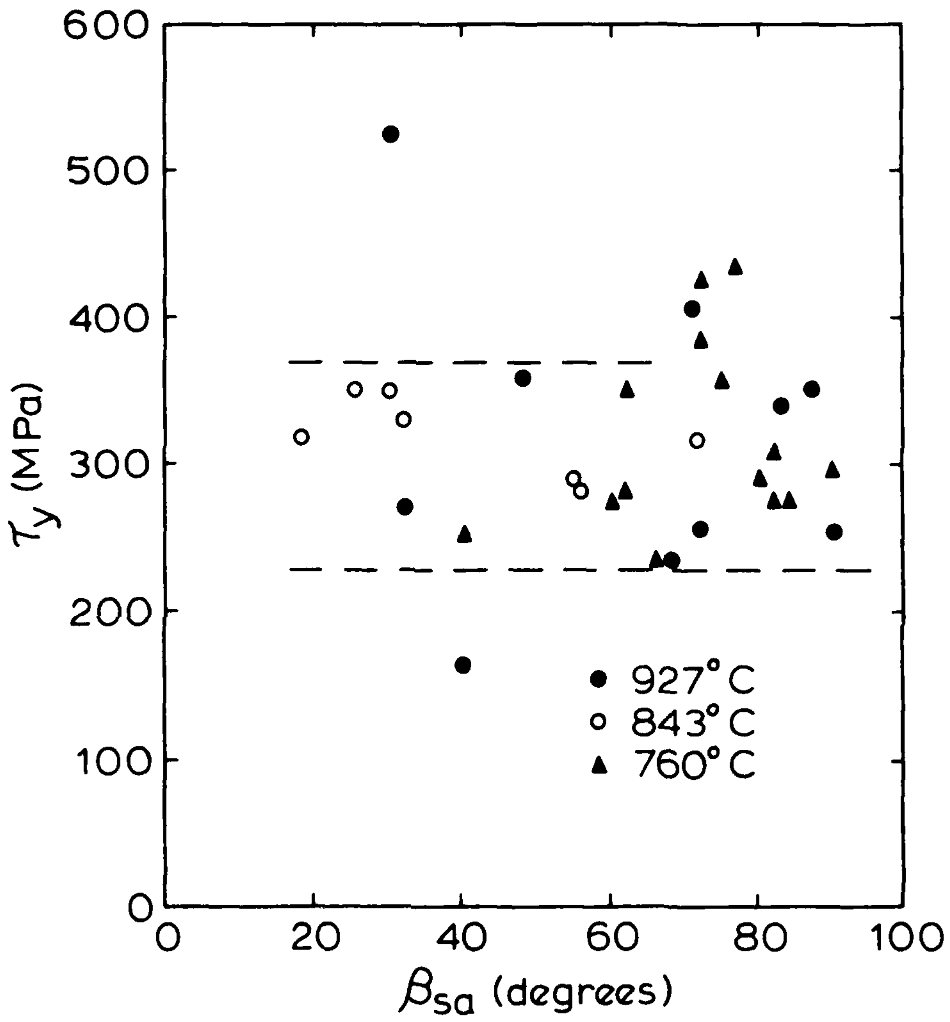

Fig. 12. The dependence of the critical resolved shear stress τ_y and the angle β_{sa} between the stress axis and the α-β interface normal.

significantly the yield stress, which is a bit surprising. In addition, no strong dependence of σ_y or τ_y on β_{sa} exists at relatively constant (±15°) values of β_b and β_s. The possibility that $\tau_y = f(\beta_{sa})$ but only at constant β_b was also explored and only at $\beta_b < 30°$ was there an indication of any relationship and then only a weak one existed. Figure 13 shows that there is an influence of β_s (β-normal to slip-plane normal angle) on τ_y only near $\beta_s \simeq 80$-$90°$. This reflects the ease of slip parallel or nearly parallel to the β lamellae ($\beta_s \simeq 0°$-$10°$) compared to that when the slip must shear to β lamellae ($\beta_s \gtrsim 10°$). Within the limitations of the data, there is also no significant dependence of τ_y on β_s at constant values (±15°) of β_b and β_{sa}. Thus we conclude that, on an individual basis, β_s and β_{sa} do not significantly affect τ_y or σ_y.

DISCUSSION

(a) On the Criteria for Yielding and Flow

The alignment of two phases (or three if one considers the interface phase) as parallel lamellae in this α-β Ti alloy results in deformation behavior which is quite unique when compared to that of single phase or particle hardened multiphase single crystals. It is well established that in Ti alloys both the α and β (or α') phases are ductile and that the α-phase is softer with slip initiating in the α-phase and impinging on the harder β-phase. However, slip initiated in the α-phase may not shear the harder β-phase. In this case, a more appropriate yield criteria would require that <u>macroscopic yielding occurs when a slip system</u>, once activated in the α-phase, <u>has the ability to shear the β-phase</u>. According to this yield requirement, a colony which deforms by slip must shear both the α and β lamellae, and the Schmid's Law will <u>not</u> be obeyed (this is an incorrect criteria). Macroscopic yielding does <u>not</u> occur simply because a critical shear stress is attained on a given α-phase

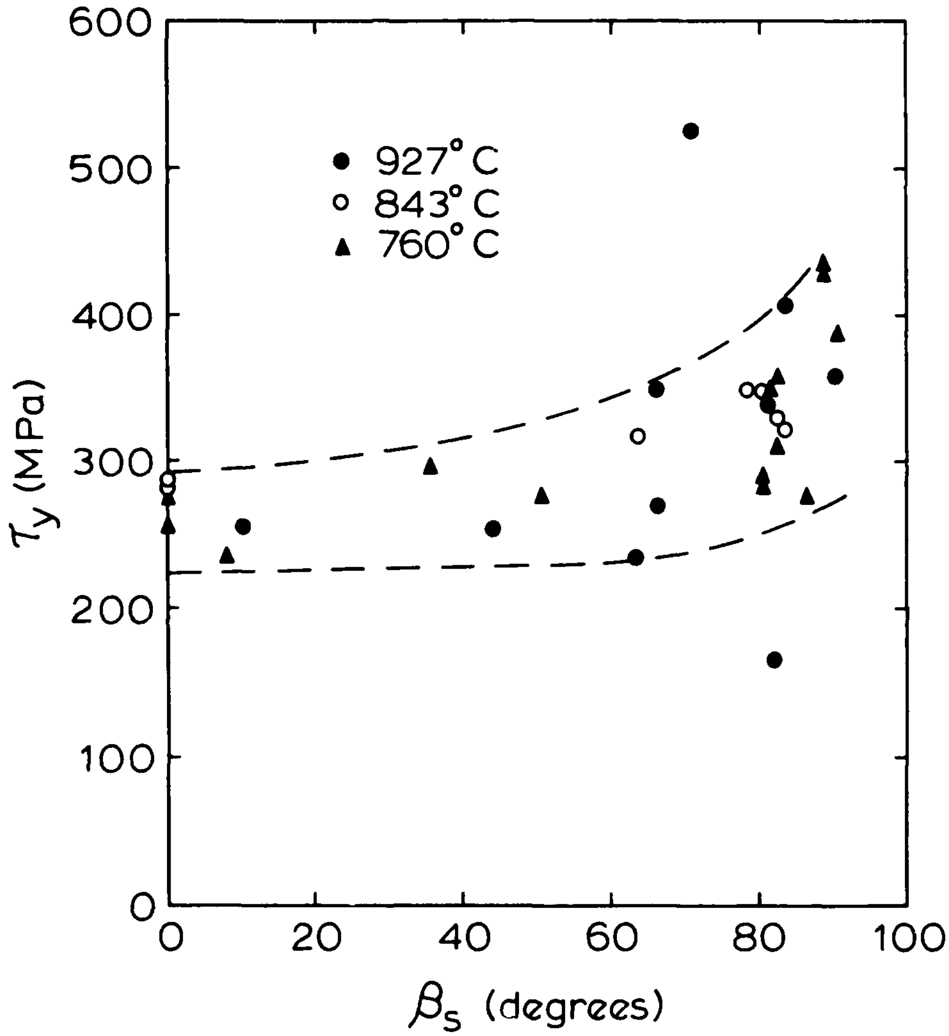

Fig. 13. The dependence of τ_y on β_s, the angle between the slip plane normal and the normal to the α-β interface.

slip system. Such a slip system should be activated but may not shear the β-phase; in this case only microstrain would be observed. The exception, of course, is slip parallel to the β lamellae for which Schmid's Law is obeyed and $\tau_y \approx 270$ MPa for the $\{10\bar{1}0\}$ prism slip.

The specific yield criteria for a colony should take into account the "shearing ability" of a given slip system which impinges on the β lamellae as well as the fiber stresses[11] which must exist in the β due to the external stress. We expect that the shearing ability factor depends on the effectiveness of a given α-phase slip system in generating a stress state in the β which causes yielding. It thus seems reasonable that the ability of a given slip system to shear the β lamellae should depend on slip line length. In the case of pearlite, this translates into a dependence of yield/flow stress on interlamellae spacing.[10] In the present study, slip line length may be reflected in the orientation of slip to the α-β interface, particularly in the angles β_b and possibly β_s. The effects of β_b and β_s on the yield stress will be discussed later.

(b) <u>On the Flow Criteria and the Observed Behavior</u>

Given the shear-the-β-phase criteria, then the rather unique relationships between observed yield stress behavior, slip morphology, and work hardening rates are a natural consequence. Consider two colonies. Colony A deforms macroscopically at a low yield stress, exhibits low work hardening, and planar, non-uniform slip. In contrast, Colony B has a high yield stress, high work hardening, and exhibits fine, uniform slip. We would predict that the <u>first</u> slip system to be activated in the α-phase of Colony A has a <u>good</u> "shearing ability" so that the β lamellae will be sheared even at the low applied stress. Slip on the most highly stressed single slip system then occurs both macroscopically <u>and</u> microscopically in Colony A, and, like the early stages of age hardening, such slip tends to be planar and confined to those planes on

which dislocations have previously passed in shearing the β-phase. The result is that Colony A exhibits a low yield stress, planar, non-uniform slip and low work hardening. It is Colony A behavior which leads to easy crack initiation in α-β Ti alloys[1-6], and which also results in coarse slip and low yield stresses in coarse pearlite[11] (in which case the relatively long slip distances[10] are critical to good shearing ability).

In contrast to Colony A, the behavior of Colony B is controlled by a poor "shearing ability" of the most highly stressed slip systems (i.e., large value of $\cos\phi\cos\lambda$). Activation of slip system with a large Schmid factor in the α is not sufficient for Colony B to deform if that slip cannot penetrate the β lamellae. Two possibilities exist: (1) slip still occurs macroscopically on a highly stressed system of poor shearing ability but only after a very large shear stress is applied (this would be the case for fine pearlite behavior[11]) or (2) slip occurs on the third or fourth most highly stressed system which happens to have a good ability to shear the β-phase. Both situations require a large applied stress and therefore result in a high axial yield stress. Several slip systems in the α-phase are stressed above yielding in both cases*, and multiple slip in the α-phase is expected to occur prior to and during macroscopic yielding and flow. Multiple slip will obviously result in uniform flow, and a relatively high work hardening which accompanies the high yield stress. Schmid's Law will be an especially poor yield criteria for Colony B.

The application of the examples of Colonies A and B to the observed behavior permits one to understand, at least qualitatively, why the colonies tested exhibit such a wide range of behavior. For examples, samples 23 and 24

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*We assume that microslip in the a-phase obeys a critical resolved shear stress criteria. For $\{10\bar{1}0\}$ slip, τ_y = 270 MPa from slip parallel to β data. Basal and pyramidal yield stresses can be estimated by assuming that τ_y in α must be less than the smallest observed yield stress for an α-β colony for that slip system. Thus τ_y for (0001) in α is ≃ 290 MPa (samples 23a, 28, 29, 31, 32) and τ_y for $\{10\bar{1}1\}$ slip in α is ≲ 275 MPa (samples 4a, 4b, 17a).

in Fig. 6 exhibit the same type of slip, (0001) in this case but with much different yield stresses work hardening rates. In sample 23, the macroscopic slip plane is the most highly stressed and should be the only active slip system (Colony A behavior). Sample 24 also slips on a (0001) but two other slip systems [$(1\bar{1}01)$ and $(01\bar{1}1)$] should have been activated, given the large shear stresses on these systems (Colony B behavior). Other similar examples applying Colony A vs. Colony B behavior and involving $\{10\bar{1}0\}$ slip and to some extent $\{10\bar{1}1\}$ slip are available by careful examination of the data in Table I; several colonies, however, do not appear to behave in either the Colony A or the Colony B manner.

If shearing the β lamellae is the controlling criteria for flow, then the strength of the β barriers should be affected in the observed data. The α-β microstructures resulting from the 760°C and 843°C annealing treatments are so similar (10% β and 12% β, respectively) that it is not surprising that samples from these two heat treatments behave almost identically. However, colonies given the 827°C heat treatment (microstructure is α-18% orthorhombic martensite, internally twinned[13]) exhibit roughly the same behavior with respect to the microstructural parameters as did the other samples. Thus, we conclude that the deformation behavior of the individual colonies is not a sensitive function of the flow behavior of the harder phase.

(c) On the Influence of Microstructural Parameters

The previous section indicates that the yielding and flow of individual colonies with aligned lamellar microstructures is controlled by the ability of slip, once activated in the softer phase, to shear the harder phase. If so, then the ability of a given slip system to shear the harder phase should be reflected in a dependence of the yield stress on certain microstructure parameters. Figures 10 and 11 show that the yield strength of the individual α-β colonies is influenced by the orientation of the slip direction with

respect to the β lamellae, even if β_s and β_{sa} are variable. Both the axial yield stress σ_y and the critical resolved shear stress τ_y increase as the orientation of the slip vector tends toward being normal to β lamellae (i.e., as $\beta_b \rightarrow 0°$). Conversely, the lowest values of σ_y and τ_y occur when slip is parallel to the β ($\beta_b = 90°$). Our data indicates this trend is independent of heat treatment and therefore this trend is independent of whether the lamellae are predominantly β or martensitic α'. It is also interesting to note that the influence of τ_y or σ_y on β_b appears to be independent of which slip system is active.

In contrast to some beliefs, the alignment of slip in the α with the slip direction in the β according to the Burger's orientation relationship does not appear to be a major factor in determining yield strength. Such alignment should exist for the α-β microstructures but not for the α-α' microstructures in which the α' is internally twinned.[13] As previously noted, the α-α' material behaves much like the α-β microstructure. There should be no interface phase present after the 843°C and 927°C heat treatments and little, if any, after the 760°C heat treatment. Thus, any potential slip alignment effects should not have been masked by the interface phases.

The absence of any apparent direct dependence on the yield stress solely on the orientation of the β lamellae to the stress axis (see Fig. 12) is not expected. The dependence, if any, must therefore be indirect. Discounting slip parallel to the β-phase, the yield strength of individual colonies is also not dependent solely on the orientation between the active macroscopic slip plane in the α-phase and the β lamellae for $\beta_s < 80°$ (see Fig. 13). In both of these cases, the reader should recognize that the yield stress may depend on β_{sa}, β_s and β_b but in some interdependent and complex manner.

The relationship between σ_y and τ_y and the angle β_b (see Figs. 10 and 11) suggest that the slip line length in the α-phase may be a factor. If edge

dislocation slip length ℓ_s were measured along the slip direction, then $\ell_s \propto (\cos\beta_b)^{-1}$, and τ_y should increase with decreasing β_b (i.e., decreasing slip line length) in a manner analogous to decreasing lamellae spacing in pearlite.[10] A similar conclusion is reached if one assumes a dislocation pile-up consisting of mixed dislocations parallel to the β lamellae. In this case, a pile-up length ℓ'_s depends on β_s, β_{sa}, and ϕ* with the relationship $\tau_y \propto (\ell'_s)^{-\frac{1}{2}}$ being roughly obeyed by most of the data. Note that the yield stress does now depend on β_s and β_{sa} (and ϕ) but in complex manner.

(d) On the Role of Elastic Interaction Stresses and the Ankem-Margolin Calculations

In a very recent study, Ankem and Margolin carefully calculated the elastic interaction stresses which arise at the α-β interfaces of the lamellae in the present Ti alloy. The calculations are based on the crystallography of the α and β phases, and, in particular, on the alignment of slip planes and directions between the two phases. The calculations show that the interaction stresses at the interface are significant only for (0001) slip and, given (0001) slip, the stresses are largest when the stress axis lies in or close to the interface (β_{sa} = 90°) and 40° inclined to the pole of the basal plane (ϕ = 40°). According to Ankem and Margolin, the interaction stresses could be of the order of 1/3 of the τ on a specific (0001) plane which is favorably oriented. As such, these stresses could account for at most only one-half of the differences in τ_y among the colonies exhibiting (0001) slip macroscopically.

Although the interaction stresses must exist at the α-β interfaces, as Ankem and Margolin have correctly identified, the question remains: do the interaction stresses significantly affect macroscopic yielding and flow of

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*$\ell'_s \propto (\sin\psi)^{-1}$, where $\psi = \tan^{-1}[\frac{-\cos A}{\cos\beta_s}]$ and $A = \cos^{-1}[\frac{\cos\phi - (\cos\beta_{sa})(\cos\beta_s)}{\sin\beta_{sa}}]$.

α-β colonies? The present data indicates no and for a number of reasons. As indicated in Table I, Fig. 4, and Figs. 10-13, there is nothing unique about (0001) slip compared to $\{10\bar{1}0\}$ or $\{10\bar{1}1\}$ slip. In fact, the largest differences in τ_y are observed not for basal slip but prism slip (see Table I and Fig. 4). Furthermore, the yield stress effects are as pronouned (see Fig. 4) for the α-α' microstructure as for the α-β microstructure which must be the basis for the Ankem and Margolin analysis.* In addition, the yield stress for colonies which should show the maximum interaction stress (i.e., (0001) slip, $\beta_{sa} \simeq 90°$, $\phi \simeq 40°$) experimentally exhibit a yield stress $\tau_y \simeq 320$ MPa (samples 23, 25, 29, and 31 with ϕ = 48-56° and $\beta_{sa} \simeq$ 82-90°). However, other samples showing basal slip yield at both lower and higher τ_y even though, given the values of ϕ and β_{sa}, the interaction stresses should be smaller (for example, τ_y = 304 and 288 MPa for samples 28 and 32, respectively, but τ_y = 427 and 446 for samples 25 and 30, respectively). Thus, if all of the data is considered, there is no correlation between the interaction stresses at the α-β interface and the macroscopic yielding behavior. This is probably due to the fact that such interaction stresses are very short range, probably decaying exponentially with distance from the interface. General yielding and flow of a colony should be controlled roughly by the average state of stress across the α and β lamellae and not by the maximum magnitude of a local stress (this is assuming that the propagation of slip, as opposed to initiation, is rate controlling).

SUMMARY

Individual colonies comprised of aligned lamellae of ductile phases (the α and β phases of a Ti alloy, in this case) exhibit stress-strain

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*At the time of their analysis, Ankem and Margolin did not have access to all of the present data, especially the α-α' results.

behavior which is critically dependent on the ability of a slip system, once activated in the softer α-phase, to shear through the harder β-phase lamellae. This "yield criteria" manifests itself in experimental behavior in which: (a) the critical resolved shear stress for yielding varies greatly from colony to colony and Schmid's Law is not obeyed (incorrect yield criteria); (b) an increase in yield stress is usually accompanied by an increase in work hardening rate; and (c) planar, non-uniform slip dominates in colonies which yield at low stresses while fine, uniform slip occurs in high strength colonies. This behavior appears to be independent of slip system and of changing the microstructure from α-β to α-α' (martensite). Relating the observed results to colony orientation parameters indicates that the yield stress of a colony increases as the slip direction of the active macroscopic slip system in the α-phase tends toward being normal to β-phase lamellae. This effect appears to be related to the slip line length for a specific slip system in the softer α-phase. Discounting $\{10\bar{1}0\}$ slip parallel to the β phase (for which $\tau_y \simeq 270$ MPa), the yield stress does not depend, on an individual basis, on the orientation of the β lamellae to either the stress axis (β_{sa}) or to the active macroscopic slip plane (β_s). However, complex inter-relationships between τ_y, β_b, β_s, and β_{sa} probably do exist.

A rigorous analysis for assessing the ability of an individual α-phase slip system to shear the β has yet to be performed. While the present experimental data indicates guidelines for such an analysis, the same data indicates there is no correlation between the interaction stress at the α-β interfaces, as calculated by Ankem and Margolin, and the macroscopic yielding behavior. Comparison of the behavior of α-β to α-α' colonies also indicates that alignment of a slip system in the α-phase with a possible slip system in the β-phase does not strongly affect the yield stress of a colony.

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The deformation behavior of individual Widmanstatten colonies comprised of aligned lamellae of ductile phases has been investigated. Based on the alpha-beta α-β Ti alloy, Ti-8Al-1Mo-1V, this study shows the existence of a large (>2X) variation in the critical resolved shear stress for yielding of individual colonies. Schmid's Law is not obeyed except for prism slip parallel to the β lamellae. In addition, colonies with a high yield stress exhibit a high work hardening rate and fine, uniform slip, while colonies (continued on back)

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with a low yield stress deform by planar, non-uniform slip. This behavior appears to be independent of, slip system (basal, prism, or pyramidal) and of microstructure (α-β vs. α-α' (martensite)). The experimental behavior is correlated to several colony orientation parameters including the: stress axis, slip plane, slip direction, and orientation of the α-β interface. The yield stress of a colony is found to increase as the slip direction of the dominant macroscopic slip plane tends toward being normal to the α-β interface.

These results indicate that the macroscopic flow behavior of colonies comprised of ductile lamellae depends on the ability of a slip system, once activated in the softer phase, to shear through the harder phase. The data also indicates that the interaction stresses at the phase interfaces are not a principal factor controlling macroscopic yielding. Finally, the alignment of a slip system in the α-phase with a potential slip system in the β-phase lamellae does not appear to affect the yield stress strongly.

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